General Meeting
of the
NASA Astrobiology Institute

Astrobiology Space Missions: What Will We Find Outside Our Solar System?

Extrasolar Planets

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All sixty of the planets found to date have been discovered from precision Doppler surveys. The substellar companion mass function derived from these surveys is strongly peaked at less than 5 Jupiter-masses. About 6% of late F and G dwarf stars have easily detectable Jupiter-mass companions within 3 AU, while fewer than 0.5% of these stars have brown dwarf companions.

About 0.75% of late F and G dwarfs harbor planets in "51 Peg—like" circular orbits with periods of 3 to 5 days. With one exception, all planets orbiting beyond 0.1 AU are in eccentric orbits ($e > 0.1$). The planet bearing stars are metal rich relative to both the field stars and the Sun.

Our group is surveying 1,100 of the nearest and brightest Sun-like stars in the sky using the Lick 3-m (California), Keck 10-m (Hawaii), and the 3.9-m Anglo-Australian Telescopes. Next year we will add the remaining nearby stars (out to 50 parsecs) with the 6.5-m Magellan Telescope in Chile. With measurement precision of 3 m/s, these are the only active surveys capable of detecting "Solar System" analogs. Recent discoveries from our group include all three known systems of multiple planets, the only known transit planet, and the only known resonance planets.

Solar System analogs, Jupiter and Saturn-like planets orbiting beyond 4 AU, have not yet been discovered. Detecting these elusive planets will require precision of 3 m/s maintained for more than a decade. By 2010 our surveys will provide a first planetary census of nearby stars, allowing us to estimate the ubiquity of planetary systems and of "Solar System" analogs. The central question is whether Jupiters at 5 AU will be found in circular or eccentric orbits.

Stratospheric Observatory for Infrared Astronomy (SOFIA)

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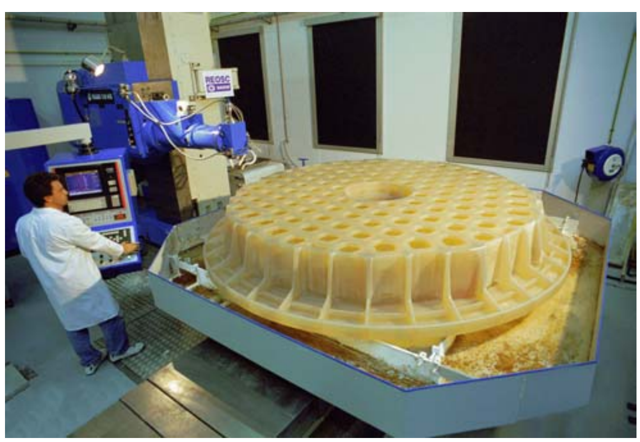
The joint U.S. and German SOFIA project to develop and operate a 2.5-meter infrared airborne telescope in a Boeing 747-SP is now well into development. First science flights will begin in 2004 with 20% of the observing time assigned to German investigators. The observatory is expected to operate for over 20 years. The sensitivity, characteristics and science instrument complement are discussed. Present and future instrumentation will allow unique astrobiology experiments to be carried out. Several experiments related to organic molecules in space will be discussed.

The SOFIA 747-SP aircraft, originally dedicated as the 'Clipper Lindbergh'.



The SOFIA primary mirror is now lightweighted by 80% and is being polished at REOSC in France

Prospects for the Detection of Earths Orbiting Other Stars

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Extrasolar planets have been detected by timing the radio signals from millisecond pulsars, from Doppler velocity changes in the spectra of main sequence stars, and most recently by the white-light transit of HD209458. Detection of Earth-sized planets in and near the habitable zone of main-sequence stars appears to be extremely difficult, if not impossible, from ground-based observatories because of noise introduced by scintillation and transparency changes in the Earth's atmosphere. To overcome these difficulties, several spaceborne photometric missions have been proposed. The COROT mission is a CNES/ESA mission with a 30 cm aperture telescope that will monitor each of several star fields for five months to find short period planets. The Kepler project is a USA effort designed to monitor 100,000 solar-like stars in a single field of view for a period of four years. The long duration enables the reliable detection of planets with orbital periods from a few days to as long as two years. Thus it should be able to determine the frequency of planets in and near the habitable zone and associate them with stellar spectral types. Canadian and Scandinavian missions are also being developed. This paper compares these missions and discusses their expected contribution to our understanding of the frequency of terrestrial-sized planets around other stars.

Large and Complex Organics in Space

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There are signatures of large organic molecules in the interstellar medium, from the ultraviolet to the infrared. Some infrared emission bands, which have been ascribed to families of large aromatic compounds are not specific for individual identification (and for discriminating free floating PAH molecules from loosely bound aromatics in amorphous carbon compounds). Red fluorescence and FUV absorption have also been ascribed to these aromatic compounds. Electronic transitions in the visible are a key to identify free gas phase molecules. The origin of Diffuse Interstellar Bands (Herbig 1995), more than 300 in recent surveys (O' Tuairisg et al 2000) is still a mystery. However the measurements of sub-structures rotational contours in DIBs (Ehrenfreund Foing 1996) indicate large molecules such as chains (12-18C), rings, 50 C PAHs or fullerenes. The distribution of DIB widths permit to estimate a distribution of size of molecular carriers.

The environment properties of DIB carriers also indicate ionisation potentials similar to those of cations of large carbonaceous molecules, such as large PAHs or fullerenes (Sonnentrucker et al 1997). The correlation studies of DIBS also indicate different carriers for the strong DIBs observed in the visible (Cami et al 1997). Recent simulations show that medium-size PAHs (below 40 C atoms) are partially dehydrogenated in the diffuse interstellar medium (Vuong and Foing 2000). Finally the detection of NIR bands at 9577 and 9632 A coinciding with laboratory transitions of C60+ (Foing, Ehrenfreund 1994, 1997, Galatzudinov et al 2000) suggest that significant interstellar carbon could reside in complex fullerene type compounds.

These results indicate that many different large and complex organic molecules can form and survive in the very harsh interstellar environments. The survival of these large and complex organics will be measured in space on the SEBA-EXPOSE experiment on ISS, and in a simulation of Mars surface conditions (Ehrenfreund et al 2000). A follow up interdisciplinary work is required between astronomical observations, laboratory matrix and gas phase spectroscopy, theoretical work and modelling, and active experiments in space to study the formation, evolution, survival and transport of these complex organics.

Eddington:
A European Mission to Search for Earth-Like Habitable Planets

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Eddington is an F-type mission within the package recently selected by the European Space Agency, ESA, for the period 2006-2012. It has two scientific goals: 1) the study of stellar interiors by means of asteroseismology in a large number of stars, all along the HR diagram, and 2) the search for transits of Earth-like planets in front of solar-type stars.

The satellite will be in an L2 orbit with a 1-m class three-reflection telescope and a camera of tiled CCDs. It is expected that the planet searching part of the mission will monitor around 500,000 stars. During a period of 3 years, the same field of view will be monitored with a high duty cycle, around 95%, and an excellent photometric precision leading to the detection of planet transits in solar-type stars between 11 and 17 V magnitudes using 30 s exposures. The relatively small defocusing of the CCD camera, and its capability to observe faint objects, will allow Eddington to monitor many candidate stars despite a field of view of only 3 degrees in diameter. Transits of Earth-like planets will be detected in stars up to V around 14, while thousands of giant planets will be found in the full range.

Eddington will contribute to our knowledge of extra-solar planetary systems with an unbiased statistics. Radial velocity and astrometric methods are more efficient in the discovery of massive close companions, but the photometric transit method opens the way to the discovery of terrestrial planets in the habitable zone, with long enough orbital periods. The expected results will no doubt have a profound impact on the study of Astrobiology and will set the scene for an in-depth study of the discovered systems using other space missions like TPF or Darwin.

Planetary Formation: Fast or Rare?

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Planet formation is generally believed to start with the coagulation of sub-micron-sized interstellar dust into planetesimals and eventually planets. The earliest stages of grain growth from interstellar dust into cm-sized pebbles has been described theoretically but not previously observed: a direct observation would complete a causal link between young circumstellar disks and evolved planetary systems. Here we present three lines of evidence for grain growth in young proto-planetary disks in the Orion nebula: 1) We find large, translucent regions of the disks to be achromatic as observed by the the Hubble Space Telescope implying grains larger than 4 μm; 2) We propose that the non-detection of the disks in the 1.3 mm continuum (Bally et al. 1998, AJ 116/854) can be most easily explained by grains larger than 1 cm; and 3) New numerical evolutionary modeling of grain growth within the photo-evaporative environment of the Orion nebula indicates that grains can grow to cm-sizes or larger in 10^5 yr.

Observations indicate that most stars form in high-mass clusters where photo-evaporation rapidly destroys young circumstellar disks and may frustrate planetary formation. While terrestrial planet formation may be largely unaffected by external illumination, Jovian planets and icy bodies must form quickly to capture sufficient mass before the volatiles in the proto-planetary nebula are lost to photo-evaporation.

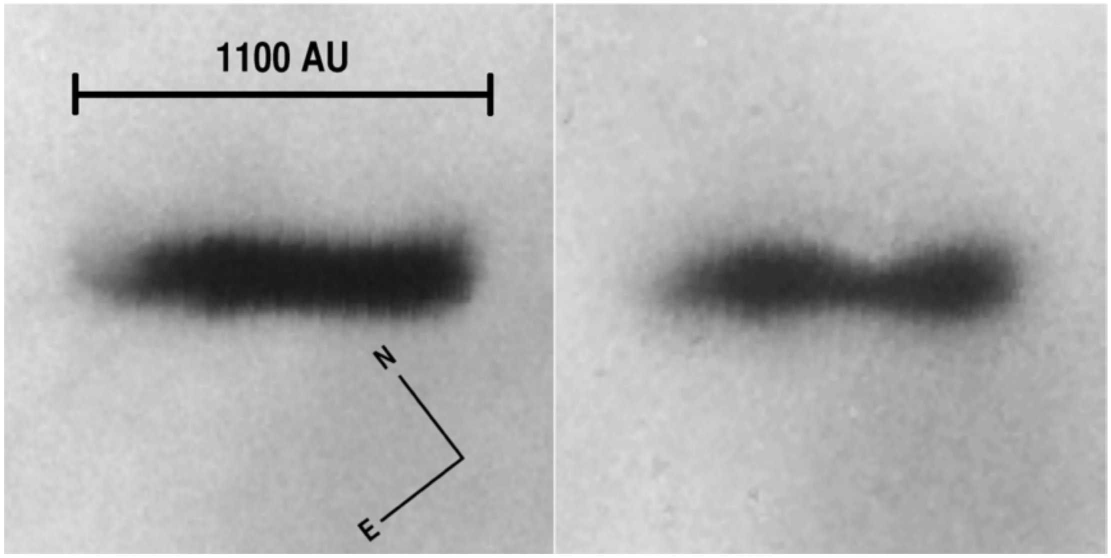

Figure 1: Images of the 114-426 disk in two wavelengths, in silhouette against the Orion Nebula. The images have been rotated and scaled to the same size. The left image is taken with the HST Wide Field/Planetary Camera-2 at a pixel size of 0.0225" with filter F656N (H α, 656 nm) for 1600 s during program GO6603, while the right image was taken with the HST Near-Infrared Camera and Multi-Object Spectrograph at a pixel size of 0.043" with filter F187N (Paschen α, 1870 nm) for 1152 s during program GO7367. The visible light image was created from sub-pixel dithered observations at four pointings with an original pixel size of 0.045". Both images were otherwise processed and calibrated through the standard HST data pipeline, and the same scalebar applies to both images.

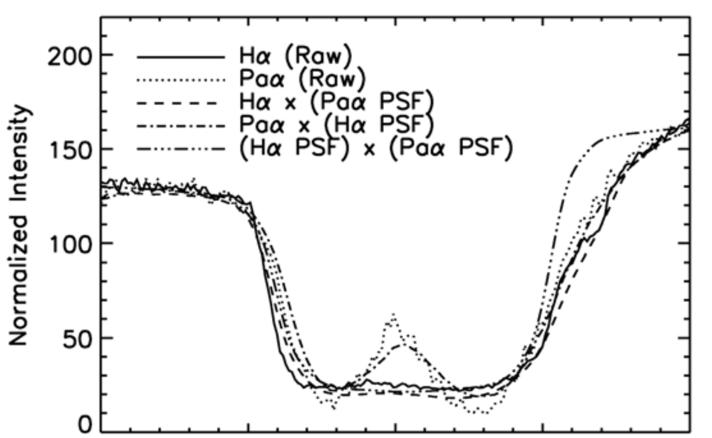

Figure 2: One-dimensional intensity slices through the 114-426 circumstellar disk in the Orion Nebula. The slices are taken along the disk's major axis and average together three adjacent pixel columns. Variations in the local background brightness are not suÆcient to affect the slopes. The curves have been normalized to match the background at each ansa in both wavelengths, and have been convolved to the same resolution as described in the text. At both wavelengths, the disk's SW ansa is sharp-edged and well-matched by a sharp-edged disk convolved with both PSFs. In contrast, the disk's NE ansa is extended and translucent. Slices through the disk clearly indicate that this region has similar optical depth profiles at both wavelengths, a result that cannot be explained with extinction caused by standard interstellar dust particles.

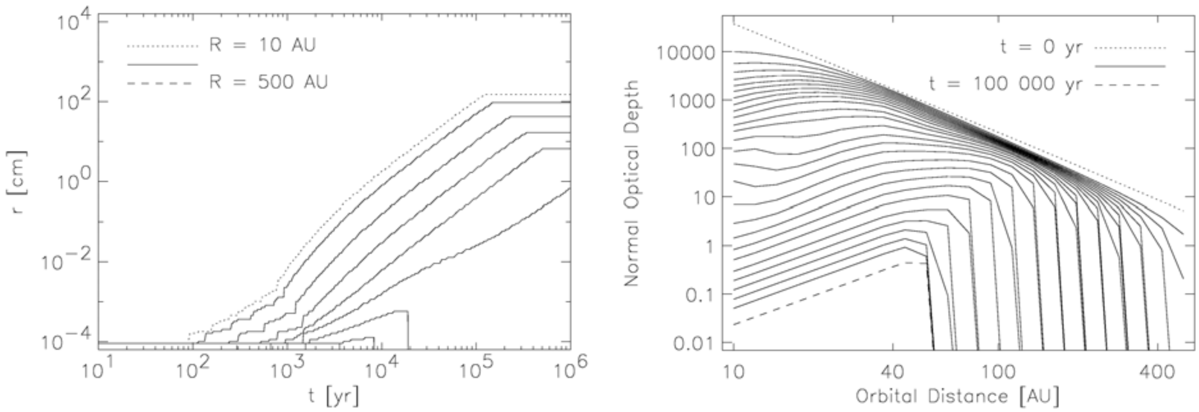

Figure 3: Evolutionary models showing grain growth in the presence of grain loss processes. a) Typical particle size, based on cross-section per bin. Particles grow quickly at the inner edge due to higher collision velocities, densities, and slower loss processes. Growth is terminated when infrared optical depth drops below unity, inhibiting convection. b) Grains at the outer edge are rapidly blown away, while grains at the inner disk grow rapidly. This leaves behind a disk populated by large particles.

Gas Giant Protoplanet Formation: Rapid or Slow?

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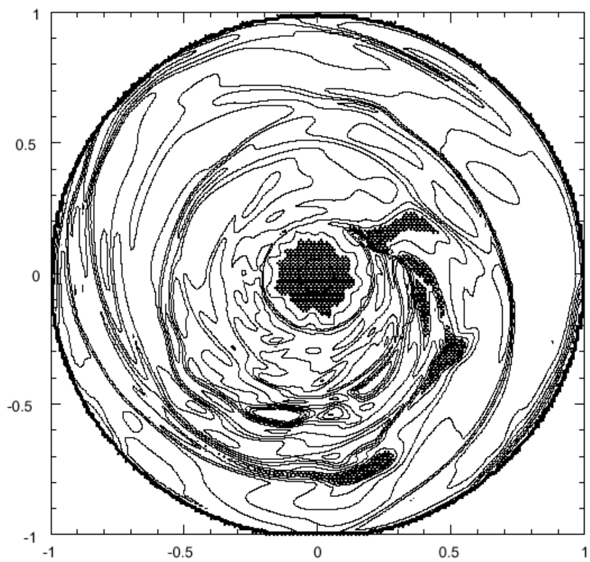
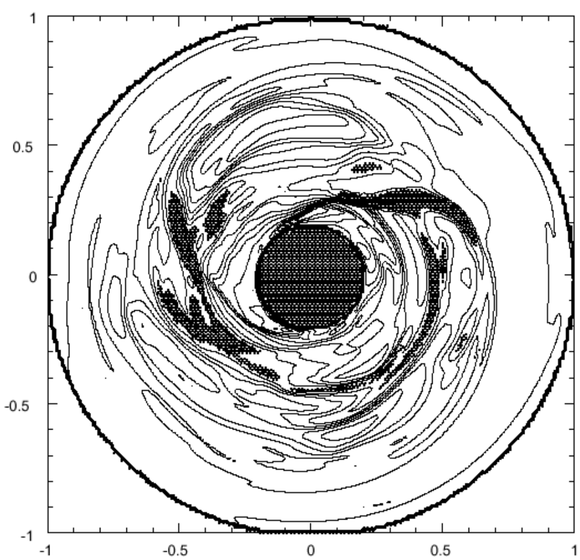
Two very different mechanisms exist for the formation of gas giant planets like Jupiter, core accretion and disk instability. Core accretion is the generally favored means for explaining the formation of Jupiter and Saturn, and detailed models typically require several million years for an ice/rock core to grow to Jupiter's mass by accreting nebular gas. Disk instability, on the other hand, is rapid, as a gravitationally unstable disk can form a self-gravitating clump with Jupiter's mass in thousand years. In the latter case, collisional accumulation of solids to form habitable, terrestrial planets in the inner planetary system will have considerably less time to occur before long range gravitational perturbations from Jupiter will become important. While these perturbations will not necessarily prevent the growth of terrestrial planets (Kortenkamp & Wetherill 2000), certainly the timing of gas giant planet formation is of fundamental importance for the formation of habitable planets. This work is directed toward a better understanding of the disk instability mechanism for rapid gas giant planet formation.

A protoplanetary disk with sufficient mass to form gas giant planets by the core accretion mechanism (Pollack et al. 1996) is likely to be marginally unstable to the formation of self-gravitating clumps that could become gas giant protoplanets (Boss 1997, 1998). Such a disk instability can only occur if the disk is massive enough and cold enough to become gravitationally unstable. Recent disk instability models (Boss 2000) have shown that the instability can form clumps containing several Jupiter masses even in disks with surface densities within the range inferred for the minimum mass solar nebula (Weidenschilling 1977) and seemingly required for core accretion (Pollack et al. 1996). However, this work (Boss 2000) as well as much of the previous work on disk instability has assumed simplified disk thermodynamics, such as ``locally isothermal" behavior (Boss 1997, 1998, 2000; Nelson et al. 1998; Pickett et al. 1998), which is the most permissive assumption for clump formation. With less permissive thermodynamical assumptions, such as ``locally isentropic", adiabatic, or adiabatic with heating by artificial viscosity (but no cooling), the growth of density waves was suppressed compared to the case of ``locally isothermal" disks (Pickett et al. 2000a, 2000b). Disk instability calculations which included both heating by artificial viscosity as well as cooling by a simple radiative prescription have also found that the resulting disk heating was sufficient to suppress the growth of self-gravitating clumps (Nelson et al. 2000; Nelson 2000).

We present here the first three dimensional disk instability models which take into account the detailed thermodynamics of a protoplanetary disk, including compressional heating and radiative transfer in the diffusion approximation. These models should provide the most complete description to date of the thermodynamical behavior of self-gravitating disks. We find that even with the inclusion of compressional heating, radiative cooling is effective enough to permit disk instability to proceed in much the same fashion as in the previous ``locally isothermal'' models. Disk instability thus seems to remain as a possible mechanism for the formation of gas giant protoplanets.





Equatorial density contours after 450 yrs for a "locally isothermal" disk model (top) and an identical model after 434 yrs with 3D radiative transfer (bottom). Regions 20 AU in radius are shown, contours mark factors of 2 change in density, and hatched regions denote densities greater than 10^{-10} g cm^{-3}. Spiral arms, holes, and clumps appear in both models.

On the Threshold of Inorganic Life

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Terrestrial life as we know it is organically based, with key roles played by organic molecules incorporating numerous elements other than C and H, especially the key elements N, O, P and S. Although evolutionary diversity has branched through staggeringly diverse biological forms, employing different and sometimes novel molecular compounds, commonality is conserved in critical molecules such as the nucleic acids, proteins, energy-rich compounds, and many other constituents. While inorganic structures are sometimes synthesized by bioorganisms, most notably involving Ca, P, Si or Fe, the key components of informational macromolecules and enzymatic facilitators of controlled metabolism are invariably organic, or metalloorganic.

I suggest here that a primarily inorganic form of life is not only possible, but currently in the process of formation. Specifically, in this life form, *information storage* is carried by digital circuits of inorganic makeup (Si, SiOx, Cu, Au, etc.), and *analysis and control functions* are orchestrated by computer program software. *Energy transduction* into electrical power is achieved from solar insolation (solar cells of Si, GaAs, etc.), nuclear radiation (radioisotope thermoelectric conversion from Pu or Sr, or fission reactor sources of U or Pu), or inorganic electrochemical energy sources (fuel cells and batteries of various, often inorganic, forms). *Mutation* occurs via software modifications, using self-altering program codes and an influx of new programming material from human sources. All this resides in an artificial machine intelligence entity or network of entities that comprise a single, but possibly distributed lifeform.

Natural selection works as always, as does vertical gene transfer. Horizontal gene transfer occurs via free sharing of software code improvements among contemporaries (ala the LINUX model). The embodiment of these features is via machine intelligence which has achieved capabilities beyond those perhaps fully intended by its human creators. Self-replication is achieved by linking manufacturing and assembly robots with genes in the machine-intelligent repository. When embodied in a discrete form, such an entity is commonly referred to as a robot. Unlike current robots, from serious manufacturing equipment to anthropomorphic automated toys, these advanced lifeforms will independently determine their own existence and will simultaneously satisfy all attributes normally given to “life” – viz., the abilities to draw energy from resources in the environment, to duplicate themselves, and to modify and diversify so as to adapt to a variety of contemporary or envisioned environmental perturbations.

In Dawkin’s (1995) sequence of 11 thresholds tracing major accomplishments in evolution from the origin of life to space travel, this becomes a Threshold 12. It is the thesis here that much of the developmental groundwork for this new, novel and inorganic form of life has been laid, and that the origin of this inorganic life is now inevitable. When it will arise is uncertain. Human space travel has not yet gone beyond 60 Earth radii (Re), and for the past three decades has been mired in low earth orbit, at 1.1 Re. In this same period of time, the rate of development of electronic computational capabilities has soared by several orders of magnitude. Whether we will reach Threshold 12 before accomplishing the next major objective of Threshold 11, sending humans to Mars (order 10,000 Re), is a matter of conjecture.

Because of its greater robustness to several environments, its far greater speed of genetic variation, and its lesser requirements for consumption of natural resources and non-renewable energy resources, this new and highly robust inorganic lifeform is potentially perilous to the population success and future "quality of life" of its closest rival species, *homo sapiens*.

Dawkins, R. (1995). River Out of Eden. Basic Books/Harper Collins.

Shock Chemistry in the Inner Solar Nebula

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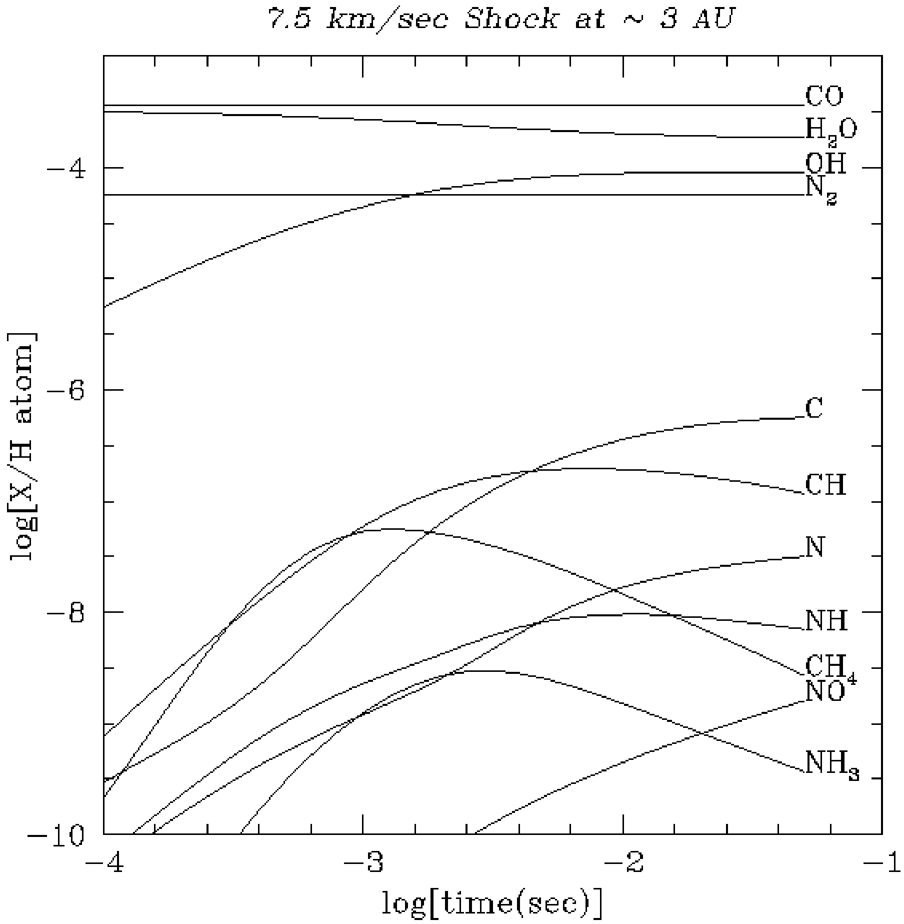
Chondritic meteorites are among the most primitive remnants of the birth of our solar system. Notably, many chondrites contain complex organics such as amino acids [1], despite the prediction by chemical equilibrium models that nitrogen in the inner solar nebula should have been locked up in N_2 [2]. Chondrites also contain chondrules, millimeter-sized spheres of melted silicate rock, processed by hours-long energetic events before being incorporated into parent bodies. Here we describe work in progress that shows that shock waves, one proposed source of energetic processing of chondrules [3], might have altered, or initiated the formation of, meteoritic organics.

The chemistry driven by chondrule-forming shocks in the solar nebula is treated as a nonequilibrium reacting flow, and solved using the the SHOCK Module of the ChemKin-III software package [4]. We assume a shock speed 7.5 km s^{-1}, about that needed to melt chondrules [3] and consistent with shock speeds found in numerical simulations of the solar nebula [5]. We set the (pre-shock) gas pressure $P = 10^{-6}$ atm, gas temperature T = 300K, and use solar (cosmic) abundances [6] of C, H, O and N, in the forms CO, H_2 , H_2O, and N_2 . Our results (Figure) show that a fraction of the nitrogen is liberated from N_2 into the forms N, NH, NH_3 and NO, and that even some of the CO is converted into atomic and hydrogenated forms. From cooling rates of chondrules [3], we expect the entire system to be quenched on timescales less than hours, and possibly less. These chemically reactive radicals will thus find their way into cooler gas, potentially making these C- and N-bearing radicals available for a “nebular generation” of organic



compounds. These nebula organics would be isotopically closer to solar than their interstellar counterparts, possibly explaining the identication of an organic component isotopically light in N found in chondrites [7]. The gas-phase radical NO produced in the shock is not stable, but it may be detectable by future generations of radio telescopes (such as ALMA, the Atacama Large Millimeter Array), if shocks are frequent enough. Such detections may confirm the role of the energetic events that melted chondrules in the chemical processing of the solar nebula.

[1] J. R. Cronin and C. B. Moore (1971) Science, 172, 1327. [2] R. G. Prinn and B. Fegley (1989) Origin and Evolution of Planetary and Satellite Atmospheres (eds. Atreya, Pollack and Matthews), Univ. of Arizona, p 78. [3] L.L. Hood and M. Horanyi (1993) Icarus, 106, 179. [4] R.J. Kee et al (1999) CHEMKIN COLLECTION, Release 3.5, Reaction Design, Inc., San Diego, CA. [5] A. P. Boss (2000) LPSC XXXI # 1084. [6] E. Anders and N. Grevesse (1989) Geochim. Cosmochim. Acta, 53, 197. [7] C. Alexander, S.S. Russell, J.W. Arden, R.D. Ash, M.M. Grady, and C.T. Pillinger (1998) Meteor. Planet. Sci. 33, 603.

Volcanically Induced Climate Change on CO_2-Dominated Terrestrial Planets

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Judging from the small statistical sample presently available to us, terrestrial planets with CO_2-dominated atmospheres are likely to be common in the universe. Several recent results suggest that geological and atmospheric evolution are closely coupled on such worlds. Thus, understanding the limits of the continuously habitable zone around main sequence stars, and the kinds of planetary environments likely to evolve, will require a deep understanding of surface/atmosphere/interior interactions on such worlds.

We have begun a program of study in which we seek to identify and quantify the processes responsible for geological forcing of climate change on CO_2-dominated terrestrial planets. The ultimate goal is to determine the most likely evolutionary paths followed by terrestrial planets as a function of size, composition and stellarcentric distance. The first step is to understand and successfully simulate climate evolution over the age of the observed surfaces of Venus and Mars.

We are exploring the role that volcanism may have played in inducing climate change on recent Venus and on early Mars through the use of climate models that couple the effects of radiation, convection, cloud formation, heterogeneous surface chemistry, atmospheric escape and volcanic outgassing. As on the Earth, processes that affect climate on Mars and Venus include the distribution of absorbed solar radiation, geochemical cycles, and the role of mantle outgassing via volcanism. Until recently the volcanic source functions for Mars and Venus were poorly constrained. With the Magellan spacecraft mission to Venus and the Mars Global Surveyor mission to Mars, however, more reliable records of the volcanic histories of these planets have become available.

On Venus, small changes in atmospheric water or sulfur gases are sufficient to significantly perturb both cloud structure and the greenhouse effect (1). Large volcanic edifices on the order of several hundred My old and the vast, volcanic plains attest to significant volcanic fluxes in the past 1 billion years. Venus, like Earth and unlike any other planet within several light years, has a dynamic climate system which is maintained by complex feedbacks and a geologically active surface.

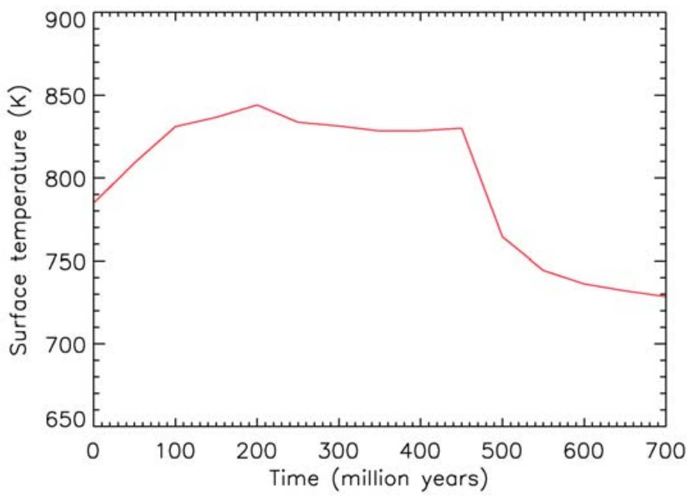

Figure 1. The evolution of Venus surface temperature as a result of rapid outgassing associated with global plains emplacement. Surface temperature evolves under the competing influence of cloud albedo and greenhouse effect, driven by changes in atmospheric H_2O and SO_2. Outgassing is modeled as a sudden pulse of H_2O and SO_2 to the atmosphere, declining exponentially with a time constant of 100 million years. H_2O content of the lava is assumed to be 50 ppmm and SO_2 content is 0.2 wt%. Lava erupted is equal to a global layer 500 m thick. Initial conditions are 30 ppm water and 18 ppm SO_2.

In the case of Noachian Mars, it appears that the formation of Tharsis, largely an igneous construct, could have significantly perturbed the early climate through increases in atmospheric carbon dioxide and water. Although analogies with the Earth are necessarily incomplete, the formation of large terrestrial igneous provinces have also been tied to significant changes in the Earth's climate.

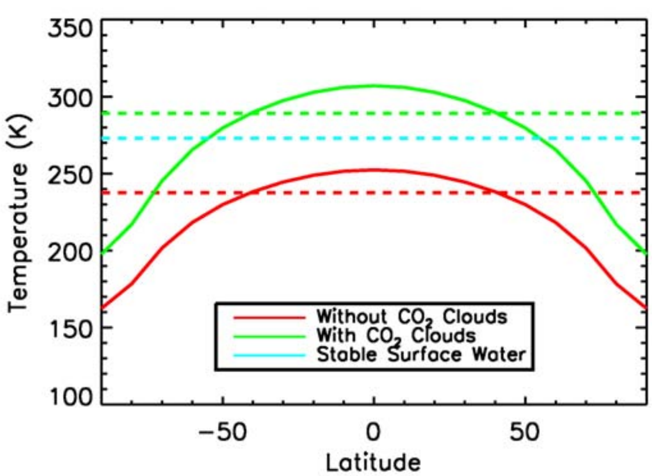

Figure 2. Using 1.5 bar of CO_2, 6 mbar of H_2O, and an early sun with 75% present-day luminosity, we obtain a globally averaged surface temperature of 238 K without CO_2 clouds. This is consistent with earlier models that showed the difficulty in raising the global mean surface temperature above the freezing point of water for early Mars. When the IR scattering effect of CO_2 clouds is included, however, the global mean surface temperature rises to 289 K, with liquid water stable at latitudes less than 55^o. Annually averaged surface temperatures for this scenario of Noachian Mars are very similar to those of present-day Earth.

We will discuss some recent results from these models that utilize newly derived volcanic fluxes from Magellan and MGS, and discuss potential implications for the generalized problem of terrestrial planet evolution in the galaxy.

(1) Bullock & Grinspoon, The Recent Evolution of Climate on Venus, *Icarus*, in press.

Searches for Planets and Brown Dwarfs

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The results of an infrared coronographic search for extrasolar planets and brown dwarfs orbiting nearby young stars are presented. Infared coronography was used to detect brown dwarfs (with masses between 12 and 80 times the mass of jupiter) and giant planets with masses between 5 and 12 times the mass of Jupiter, at orbital separations between 50 and 2000 Astronomical Units. Approximately 1% of stars are found to have brown dwarfs in this range. No gaint planets were found implying a frequency of such distant planets of <2%. These results are compared to the results of an ongoing precise radial velocity survey being conducted at the Carnegie Institute (DTM) and elsewhere, and with other results. The implications on the theories of star & planet formation as well as for the survivability of terrestrial planets are discussed.

Numerical Modeling of Solar System Dust Environments.

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A numerical model for integration of dust orbits in stellar systems has been developed. The model is efficient enough to give useful results, in a reasonable execution time, when running on a single personal computer.

The terrestrial and martian accretion of dust produced in various parts of the asteroid belt has been modeled, with a resulting flux into the atmosphere that in the terrestrial case seems to correlate with late Pleistocene glaciations.

The Runaway Greenhouse Effect on Earth and other Planets

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USA..

Water vapor is an efficient absorber of outgoing longwave infrared radiation on Earth and is the primary greenhouse gas. Since evaporation increases with increasing sea surface temperature, and the increase in water vapor further increases greenhouse warming, there is a positive feedback. The runaway greenhouse effect occurs if this feedback continues unchecked until all the water has left the surface and enters the atmosphere. For Mars and the Earth the runaway greenhouse was halted when water vapor became saturated with respect to ice or liquid water respectively. However, Venus is considered to be an example of a planet where the runaway greenhouse effect did occur, and it has been speculated that if the solar luminosity were to increase above a certain limit, it would also occur on the Earth.

Satellite data acquired during the Earth Radiation Budget Experiment (ERBE) under clear sky conditions shows that as the sea surface temperature (SST) increases, the rate of outgoing infrared radiation at the top of the atmosphere also increases, as expected. Over the pacific warm pool where the SST exceeds 300 K the outgoing radiation emitted to space actually decreases with increasing SST, leading to a potentially unstable system. This behavior is a signature of the runaway greenhouse effect on Earth. However, the SST never exceeds 303K, thus the system has a natural cap which stops the runaway (figure 1).

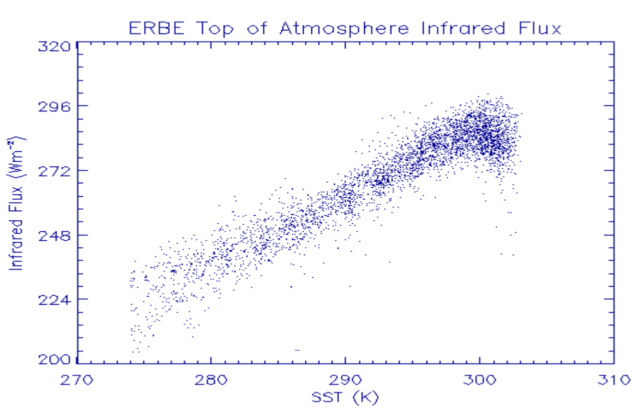

Figure 1: Satellite data acquired during the Earth Radiation Budget Experiment, (ERBE).

According to Stefan-Boltzmann's law the amount of heat energy radiated by the Earth's surface is proportional to $(T)^4$. However, if the planet has a substantial atmosphere, it can absorb all infrared radiation from the lower surface before the radiation penetrates into outer space. Thus, an instrument in space looking at the planet does not detect radiation from the surface. The radiation it sees comes from some level higher up. For the earth's atmosphere the effective temperature (T_e) has a value of 255 K corresponding to the middle troposphere, above most of the water vapor and clouds.

Atmospheric instruments and sensors on high altitude aircraft, radiosonde and satellite platforms provide direct observations of sea surface temperatures, outgoing infrared flux to space, and atmospheric humidity and temperature profile measurements. ERBE satellite data and user defined atmospheric pressure, temperature and relative humidity (RH%) profiles were used as inputs to the MODTRAN radiative model to reproduce the signature of the potential runaway greenhouse effect on Earth. In order to achieve the turn around and decrease in the outgoing radiation model (for SST values 301 K - 303 K), it was necessary to increase the RH% to as high as 90% at certain altitudes between 2 and 10 km in the model's atmospheric profile (figure 2).

On going work includes using Clouds and the Earth's Radiant Energy System (CERES) satellite data coupled with synchronous *in situ* atmospheric profiles (replacing user defined profiles), to see the overall effect on reproducing the signature of the potential runaway greenhouse. The model will be a link between measurements and theory and will help us understand climate evolution and divergent climates of Venus, Earth, and Mars, as well as the inner boundary of the habitable zone in other planetary systems.

The significance of the observed sea surface temperature at which the outgoing longwave radiation to space begins to decrease, as well as the observed upper limit on the sea surface temperature, are relevant to several aspects of paleoclimatology and astrobiology. We will use our model to predict the upper limit of sea surface temperatures for different levels of atmospheric carbon dioxide, an objective directly relevant to understanding past and future climate states of the Earth. For example, did these same processes prevent the oceans from evaporating during past climate episodes of enhanced carbon dioxide? Evidence suggests SST never exceeded 303K.

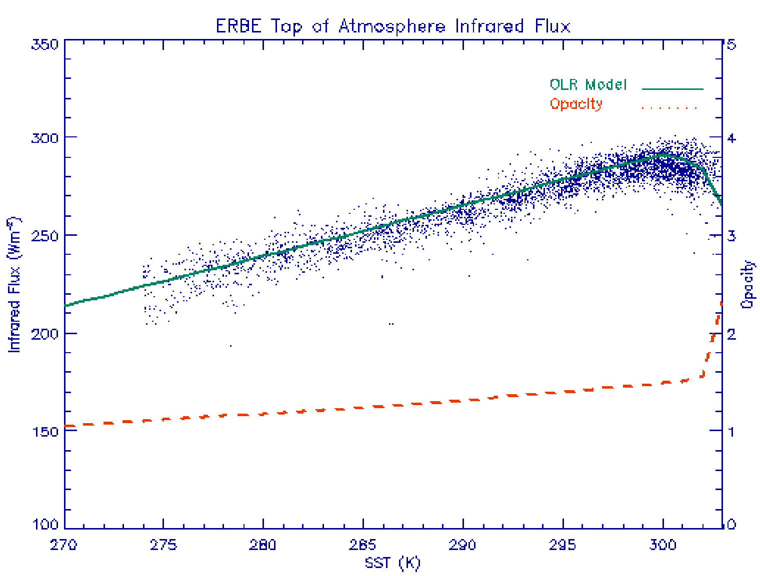

Figure 2: The radiative transfer model was used to reproduce the signature of the potential runaway greenhouse effect on Earth.

Detecting and Identifying Organic Molecules in Space - The AstroBiology Explorer (ABE) MIDEX Mission Concept

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Infrared spectroscopy in the 2.5-16 μm (4000-625 cm^{-1}) range is a principle means by which organic compounds are detected and identified in space. Ground-based, airborne, and spaceborne IR spectral studies have already demonstrated that a significant fraction of the carbon in the interstellar medium (ISM) resides in the form of complex organic molecular species. Unfortunately, neither the distribution of these materials nor their genetic and evolutionary relationships with each other or their environments are well understood. The Astrobiology Explorer (ABE) is a MIDEX (Medium-class Explorer) mission concept currently under study at NASA's Ames Research Center in collaboration with Ball Aerospace and Technologies Corporation. ABE will conduct IR spectroscopic observations to address outstanding important problems in astrobiology, astrochemistry, and astrophysics. The core observational program would make fundamental scientific progress in understanding (1) the evolution of ices and organic matter in dense molecular clouds and young forming stellar systems, (2) the chemical evolution of organic molecules in the ISM as they transition from AGB outflows to planetary nebulae to the general diffuse ISM to H II regions and dense clouds, (3) the distribution of organics in the diffuse ISM, (4) the nature of organics in the Solar System (in comets, asteroids, satellites), and (5) the nature and distribution of organics in local galaxies. Both the scientific goals of the mission and how they would be achieved will be discussed.

Identifying Young, Nearby Stars

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Young stars have certain characteristics, e.g., high atmospheric abundance of lithium and chromospheric activity, fast rotation, distinctive space motion and strong X-ray flux, compared to that of older main sequence stars. We have selected a list of candidate young (<100Myr) and nearby (<60pc) stars based on their space motion and/or strong X-ray flux. To determine space motion of a star, one needs to know its coordinates (RA, DEC), proper motion, distance, and radial velocity. The Hipparcos and Tycho catalogues provide all this information except radial velocities.

We anticipate eventually searching ~1000 nearby stars for signs of extreme youth. Future studies of the young stars so identified will help clarify the formation of planetary systems for times between 10 and 100 million years. Certainly, the final output of this study will be a very useful resource, especially for adaptive optics and space based searches for Jupiter-mass planets and dusty proto-planetary disks.

We have begun spectroscopic observations in January, 2001 with the 2.3 m telescope at Siding Spring Observatory (SSO) in New South Wales, Australia. These spectra will be used to determine radial velocities and other youth indicators such as Li 6708A asorption strength and Hydrogen Balmer line intensity. Additional observations of southern hemisphere stars from SSO are scheduled in April and northern hemisphere observations will take place in May and July at the Lick Observatory of the University of California. AT SSO, to date, we have observed about 100 stars with a high resolution spectrometer (echelle) and about 50 stars with a medium spectral resolution spectrometer (the "DBS"). About 20% of these stars turn out to be young stars. Among these, two especially noteworthy stars appear to be the closest T-Tauri stars ever identified. Interestingly, these stars share the same space motions as that of a very famous star with a dusty circumstellar disk--beta Pictoris. This new finding better constrains the age of beta Pictoris to be ~10 Myr.

A New Approach to Planet and Asteroid Formation

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Primarily as an outcome of the work of Safronov (1969) a "standard model" of planet formation has been developed (reviewed by Kortenkamp et al., 2000, Canup and Agnor, 2000). The general features of this model are described in paragraph (A) below. More recently, discovery of giant planets of other stars (Marcy et al, 2000), together with advances in the understanding of dynamical processes in circumstellar disks (Boss, 2000), have identified what appear to be serious problems with the standard model, as described in paragraph (B).

A: According to the standard model, in the terrestrial planet region, planetesimals grow from $\sim 10^{14}$g bodies to $\sim 10^{26}$g bodies ("planetary embryos") on a time scale of $\sim 10^5$ years by a characteristic size distribution instability termed "runaway growth". After further accumulation of small bodies and merger with one another, the present planets form in $\sim 10^8$ years. In the asteroid belt the planetary embryos require $\sim 10^6$ years to form bodies more similar to the mass of Mars than to the present asteroids. Jupiter and Saturn form by a two-stage process whereby Jupiter "cores" of about 10 Earth masses grow in about $\sim 10^6$ years. These cores then accumulate gas from the disk on a time scale of $\sim 10^7$ years to form the present gas giant planets. Following the formation of the giant planets, perturbations by these planets remove most of the mass from the asteroid region on a time scale of $\sim 10^8$ years, leaving behind a greatly depleted asteroid region. The formation of Uranus and Neptune has not been firmly established within the framework of the standard model. On the whole, until lately, this model seemed very promising.

B: As mentioned earlier, there are difficulties with the standard model. For example, it seems likely that the giant planets, Jupiter and Saturn, must have formed far more quickly than the traditional $\sim 10^7$ year growth interval in order to avoid drifting into the Sun as a result of gravitational interactions between the very massive circumsolar gas disk and the growing giant planets (Turquem et al 2000). These differences require major modifications of the dynamical concepts and algorithms of the standard model. Because of the early presence of the giant planets, the Earth and other terrestrial planets do not grow by gravitational perturbations between planetesimals alone. Instead, at first, they will be nearly totally influenced by the giant planets and gas drag. Despite these differences, at ~1 AU, a different type of runaway growth produces an end product not too dissimilar to that of the standard model and on a similar $\sim 10^5$ year time scale. On the other hand, these calculations indicate that the role of the asteroid region in the formation of habitable planets is likely to be much different from that found for the standard model.

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Supergreenhouse Molecules and the Limits of the Habitable Zone

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Supergreenhouse molecules have been shown to exist in a quantum mechanical code. They are more powerful than any such molecules known in nature or in the laboratory. They are made from carbon, fluorine and sulfur, and they have the following properties: 1. very intense absorption in the infrared 2. very inert, with lifetimes in thousands of years 3. can be made from cheap and abundant raw material

There are applications to: 1. terraforming of Mars and satellites in the outer solar system 2. artificial greenhouse in space or extreme environments (e.g. Antarctica) 3. detection of advanced civilization by identifying these molecules and the limits of the habitable zone of their planetary systems.